

QUARK MATTER 2015

The XXVth International Conference on Ultrarelativistic Nucleus-Nucleus Collisions

PHENIX results on low p_T direct photons in Au+Au collisions

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for the PHENIX Collaboration

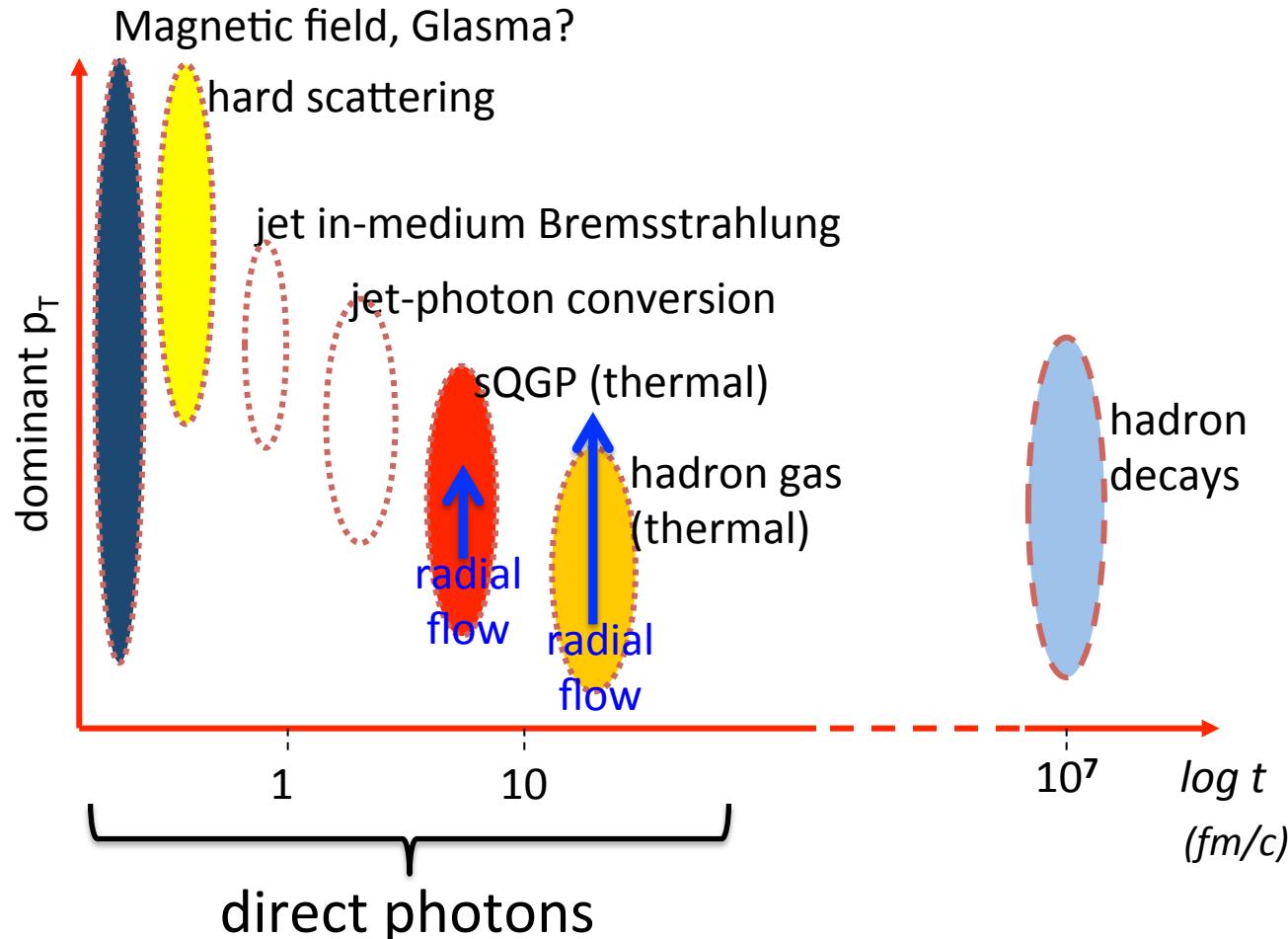
Quark Matter 2015



Outline

- Direct photons and motivation for study
- Measuring photons at PHENIX
- Results
 - Direct photon yield
 - Direct photon v_2 and v_3
- Summary and outlook

Photons Sources in Heavy Ion Collisions



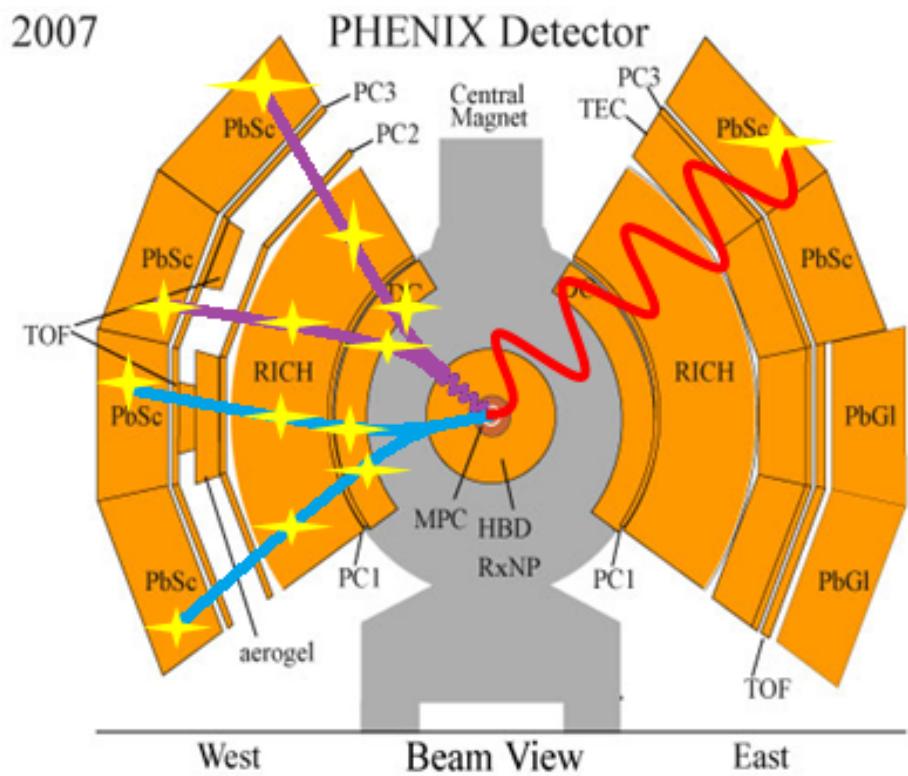
- Disentangle various sources folded with space-time evolution for a complete picture of the collision

Our Experimental Task

- Different observables
 - yields
 - v_2 and v_3
- Photon p_T in wide range: 0.4 – 20 GeV/c
- Centrality dependence
- Collision species (system size): Au+Au, Cu+Cu, d+Au, p+p
- Collision energy: 200GeV, 62 GeV, 39 GeV

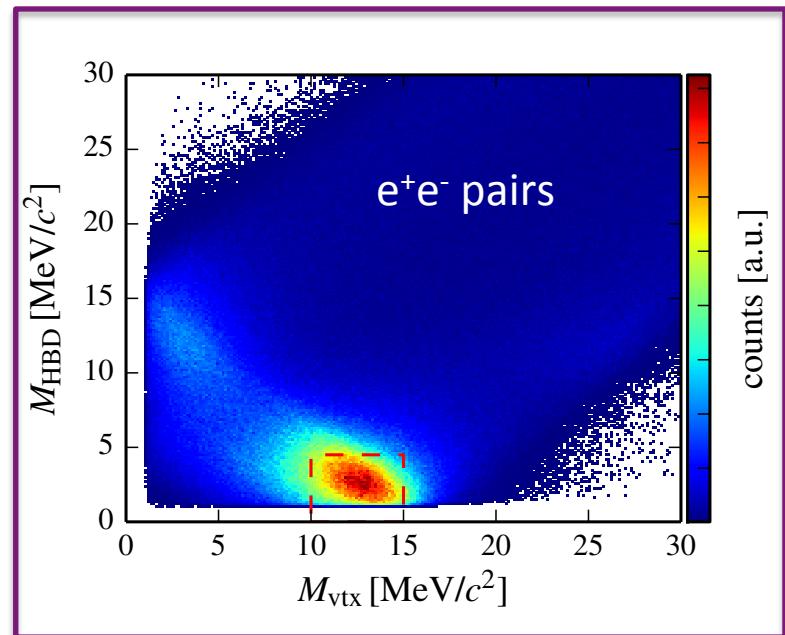
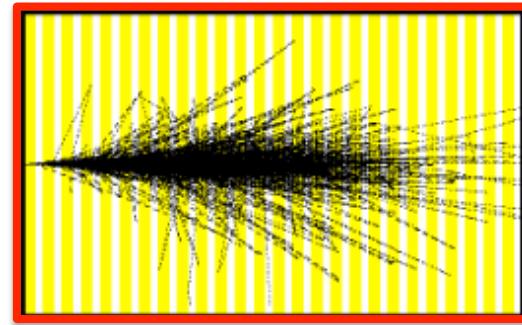
Experimental Techniques at PHENIX

- Large background from hadron decays makes analysis difficult
- 3 methods at PHENIX
 - Internal photon conversions
 - Measure virtual photons
 - Reduce background from π^0 Dalitz decays
 - External photon conversions
 - Measure real photons
 - Reduce hadron contamination
 - Photons deposit energy into emcal
 - Best at high momentum
- Allows for comprehensive measurements and cross-checks



More Experimental Details

- Photon id
 - **Emcal method**: measure photon energy deposited directly in the emcal
 - Shower shape cut
 - Charged track veto cut
 - **External Conversion method**: measure photons that convert in detector material
 - Mis-reconstruct far off-vertex particles in PHENIX
 - Exploit mis-reconstruction
 - Calculate momenta both assuming vertex origin and off-vertex origin
- Estimation of hadron decays
 - MC cocktail sim based on published measurements of yields and v_2, v_3
 - Includes $\pi^0, \eta, \eta', \omega$



Direct Photon Rates in Au+Au Collisions

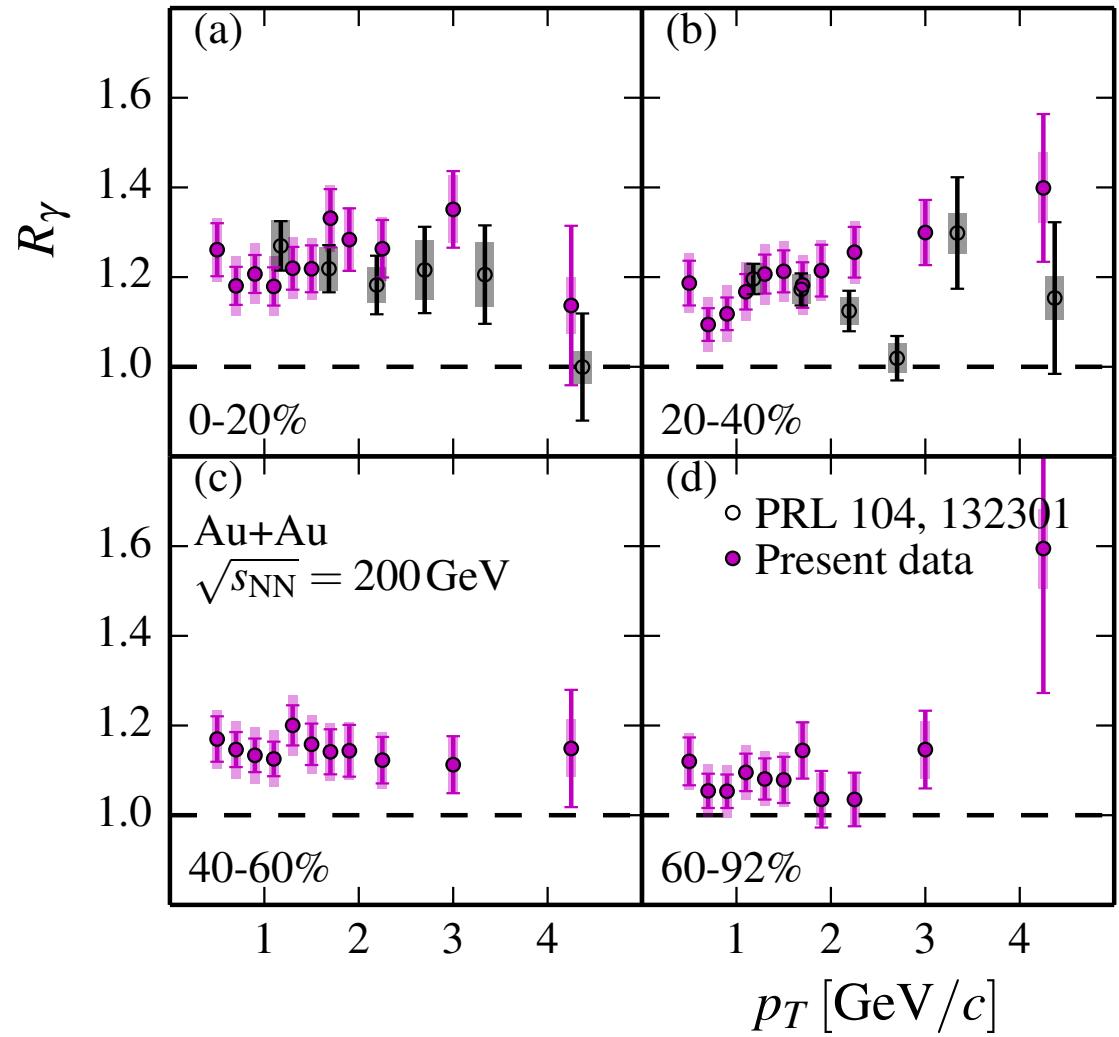
Establishing a Direct Photon Signal

PRC 91, 064904 (2015)

PRC Highlight

$$R_\gamma = \frac{\gamma^{incl}}{\gamma^{hadron}} = \frac{\left\langle \epsilon_\gamma f \right\rangle \left(\frac{N_\gamma^{incl}}{N_{\pi^0}^{tag}} \right)_{Data}}{\left(\frac{\gamma^{hadron}}{\gamma^{\pi^0}} \right)_{Sim}}$$

- External conversion method
- Observe a non-zero direct photon signal at low p_T
- Smooth centrality dependence
- Signal decreases going from most central to peripheral collisions

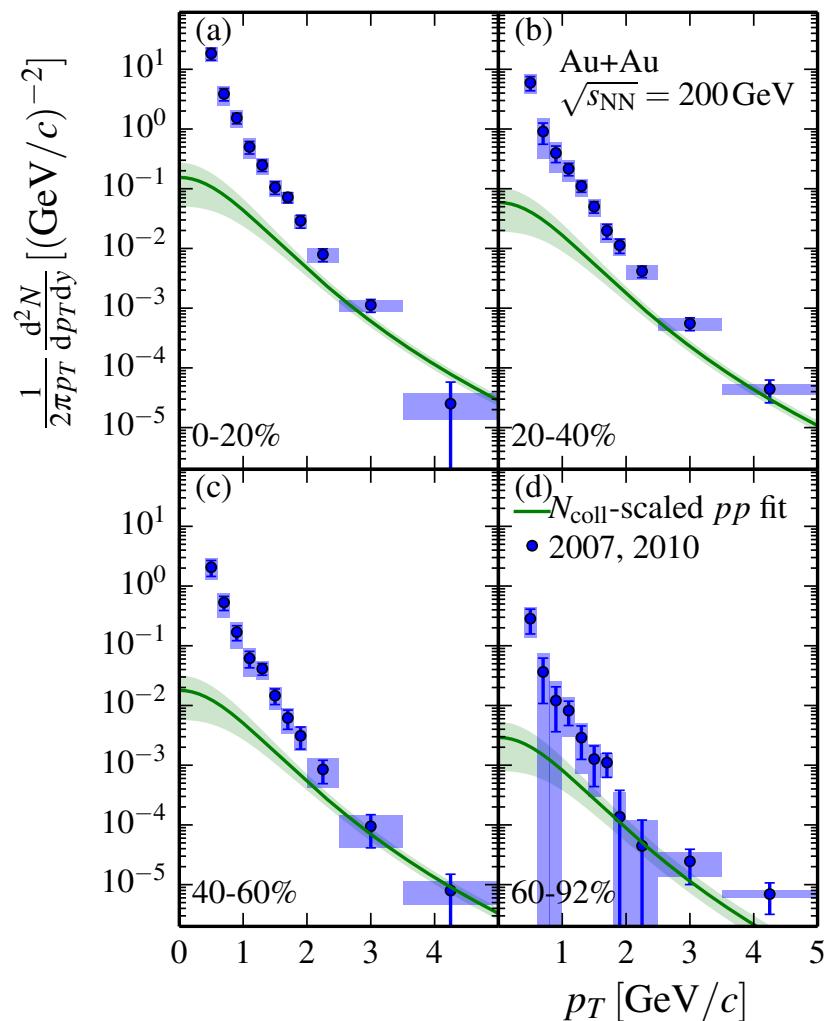
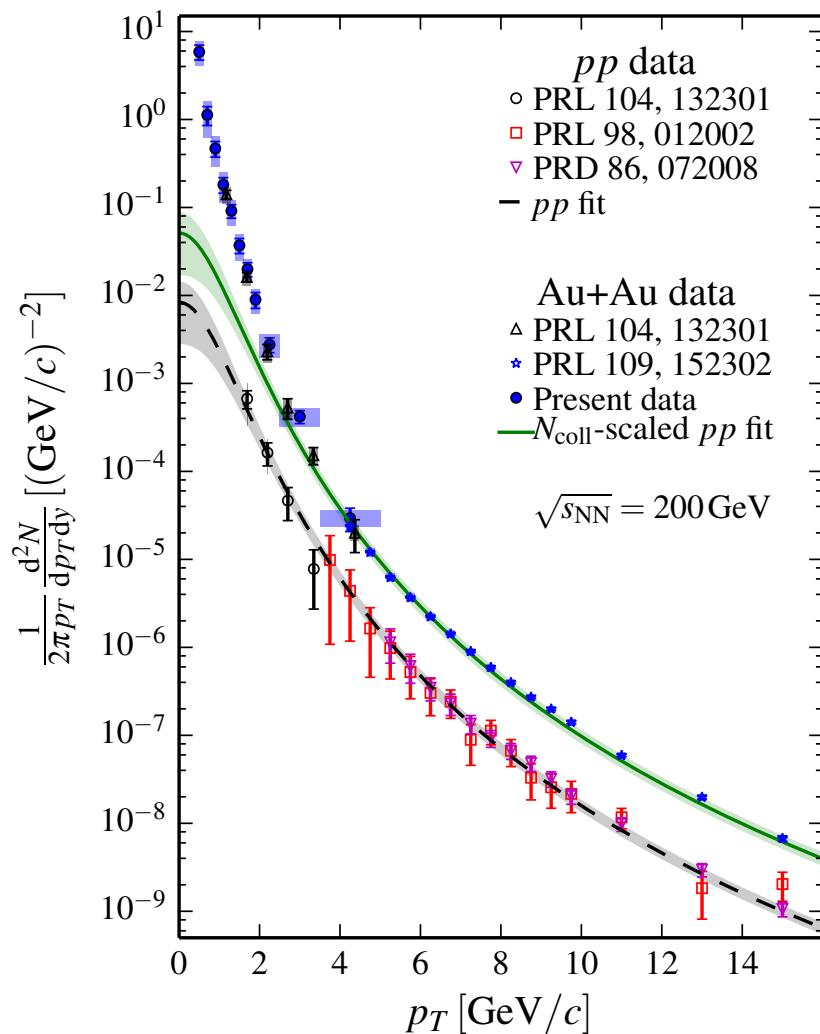


Direct Photon Yield

PRC 91, 064904 (2015)

PRC Highlight

$$\gamma^{direct} = (R_\gamma - 1)\gamma^{hadron}$$

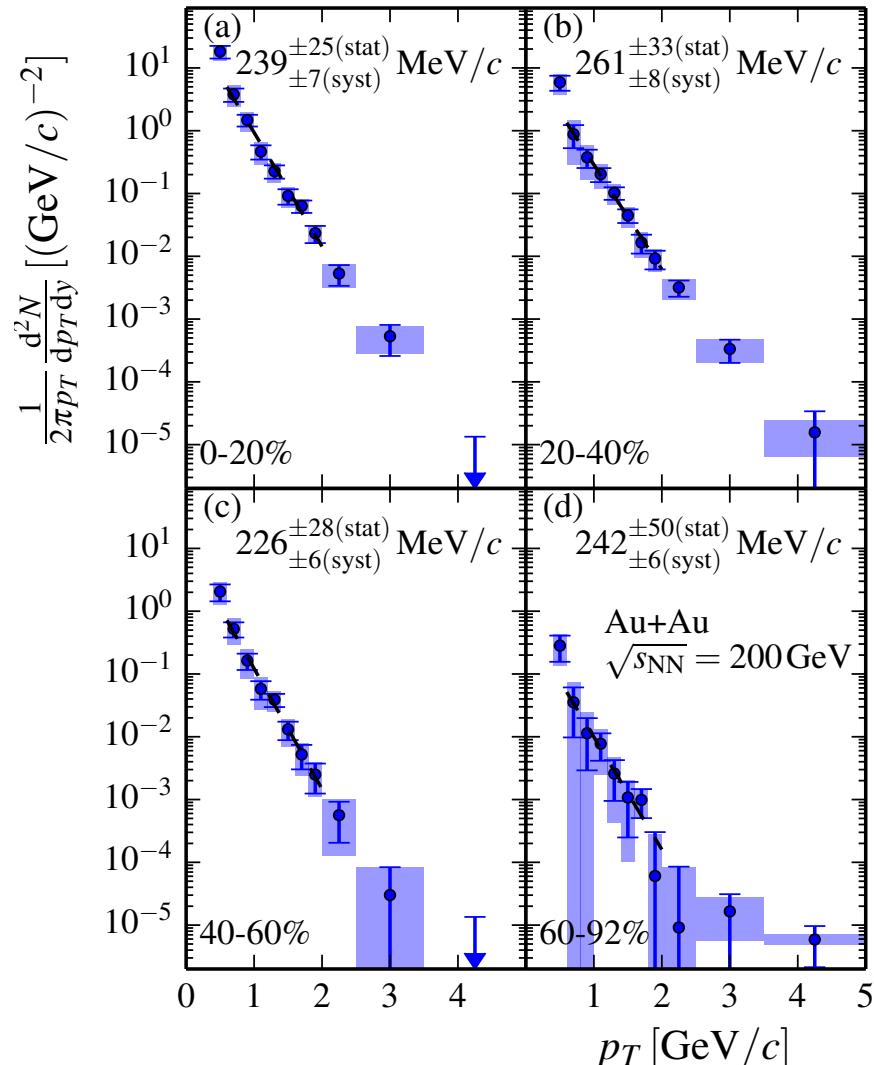


Isolating the Yield Above Expected Hard Processes

PRC 91, 064904 (2015)

PRC Highlight

- Parameterize contribution of hard scattering by fitting to the p+p yield and scaling by N_{coll}
- Subtract this estimation from the measured direct photon yield
- This isolates the low p_T excess largely thought to be due to thermal radiation



Detailed N_{part} Dependence of Yield

PRC **91**, 064904 (2015)

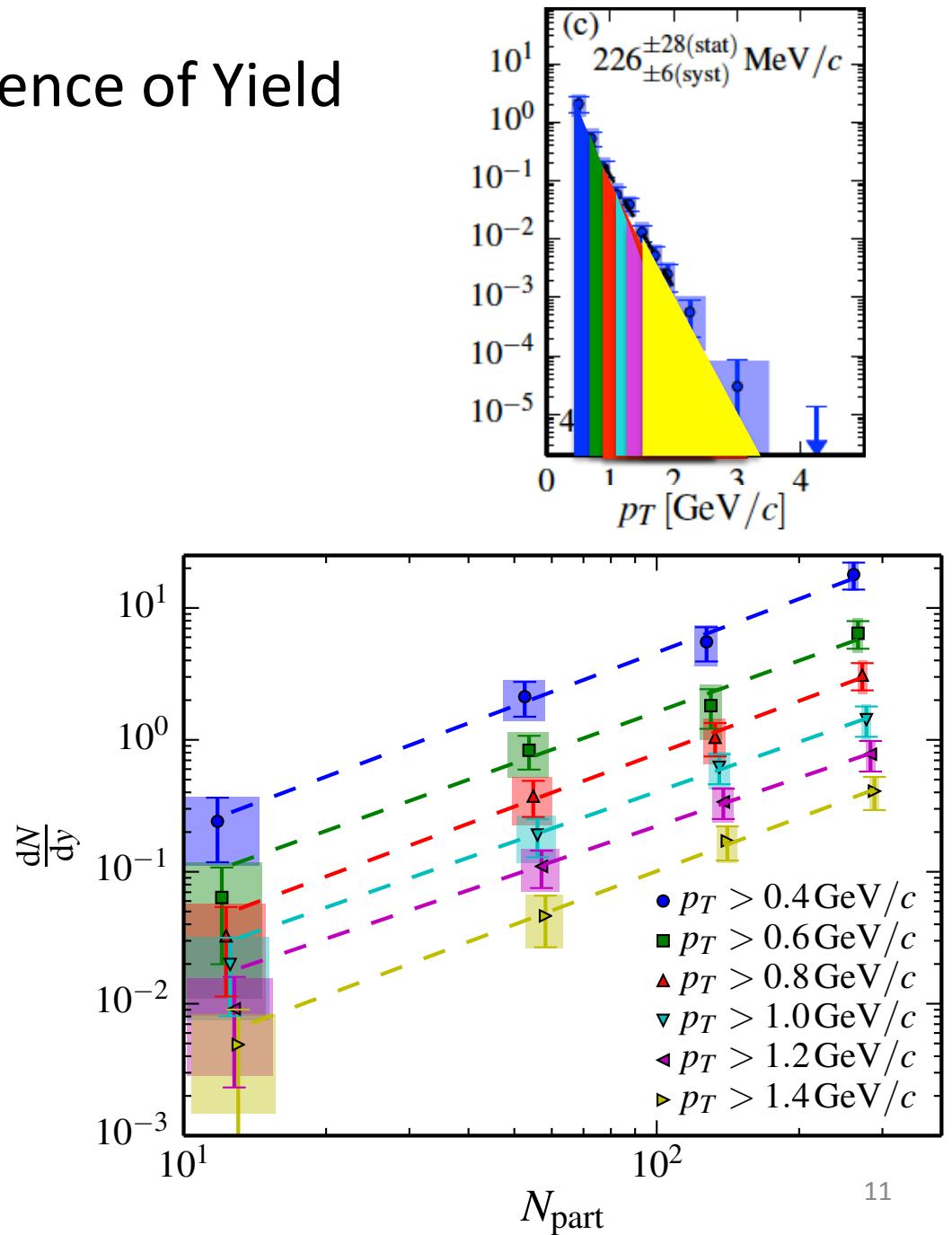
PRC Highlight

- Integrate the excess yield as a function of N_{part}
- Integrate with in different p_T ranges

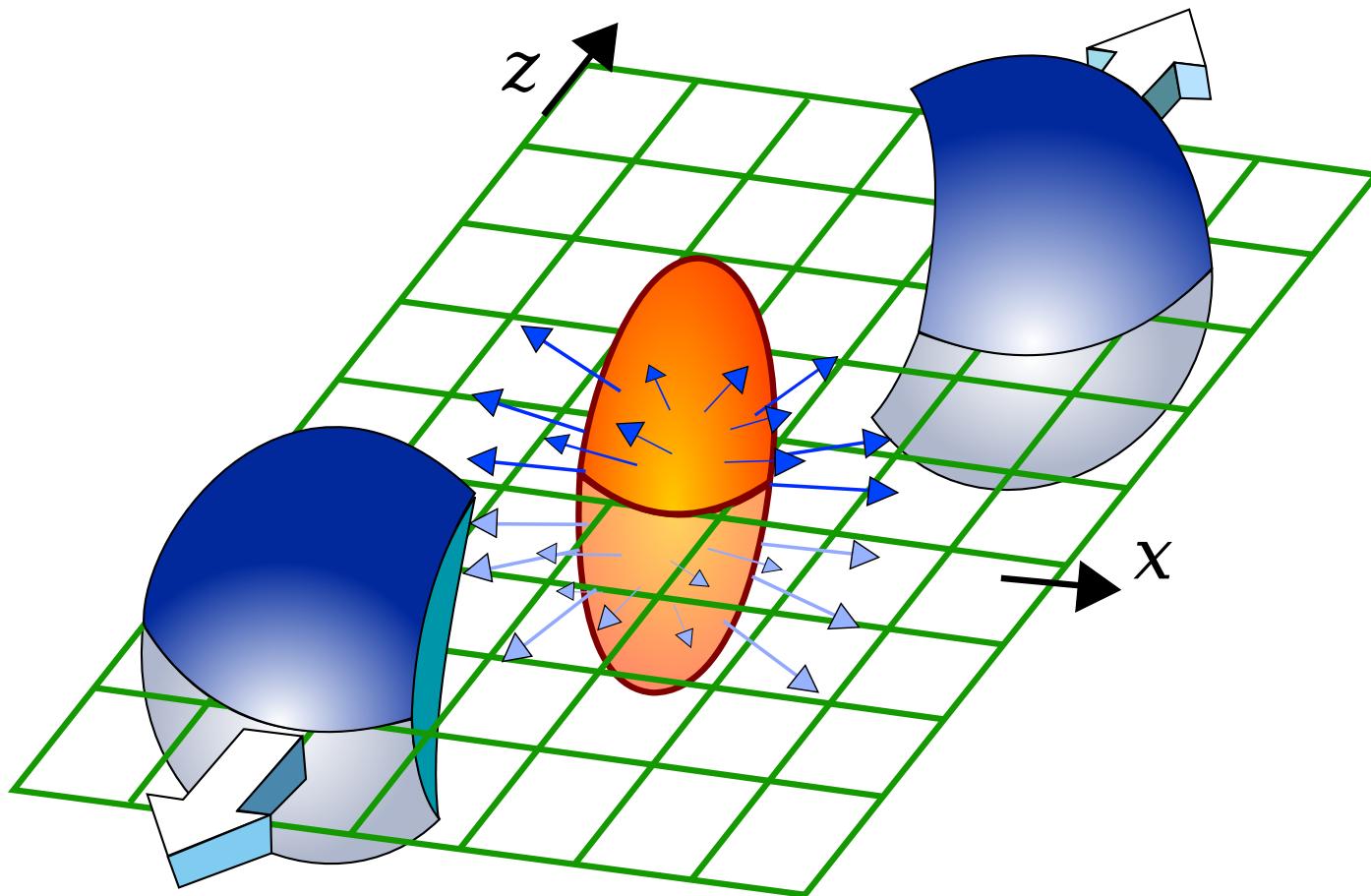
- Power law dependence observed

$$Y \propto N_{\text{part}}^{1.38 \pm 0.03(\text{stat}) \pm 0.07(\text{sys})}$$

- PRC 89 044910 (Gale, Heinz, Paquet, Shen)
 - Dependence: $Y \propto N_{\text{part}}^{\sim 1.6-1.9}$



Direct Photon v_n in Au+Au Collisions



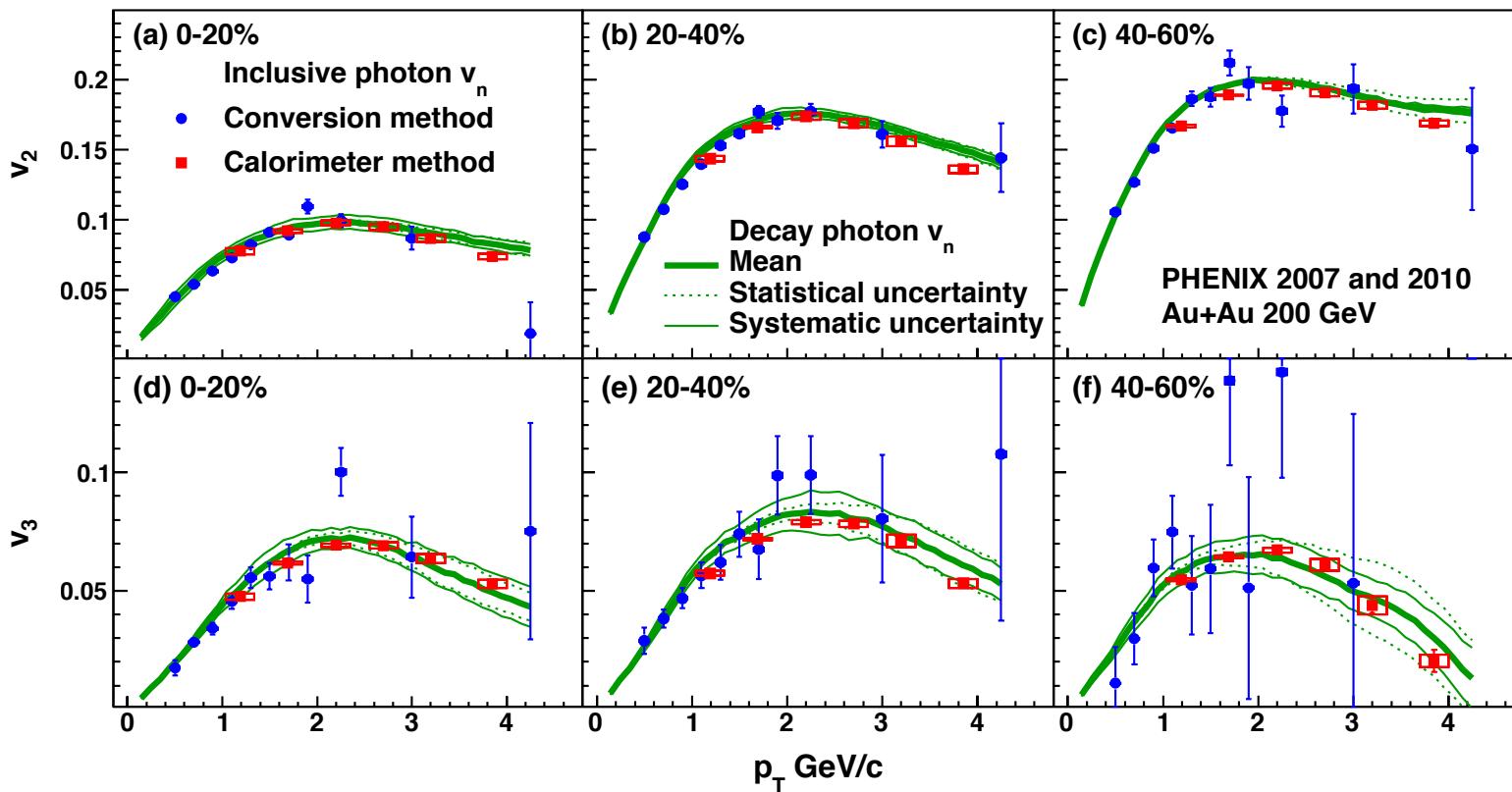
Inclusive and decay photon v_n

- Measure azimuthal distribution of photons relative to the reaction plane
- Use the two photon id techniques described (**emcal** and **external conversions**)
- Model decay photon v_n based on the measured $\pi^0 v_n$
 - Other hadron (η , η' , ω) v_n estimated from KE_T scaling

$$v_n^{meson}(KE_T) = v_n^\pi(KE_T) , \text{ with } KE_T = m_T - m = \sqrt{p_T^2 + m^2} - m$$

arXiv:1509.07758

NEW

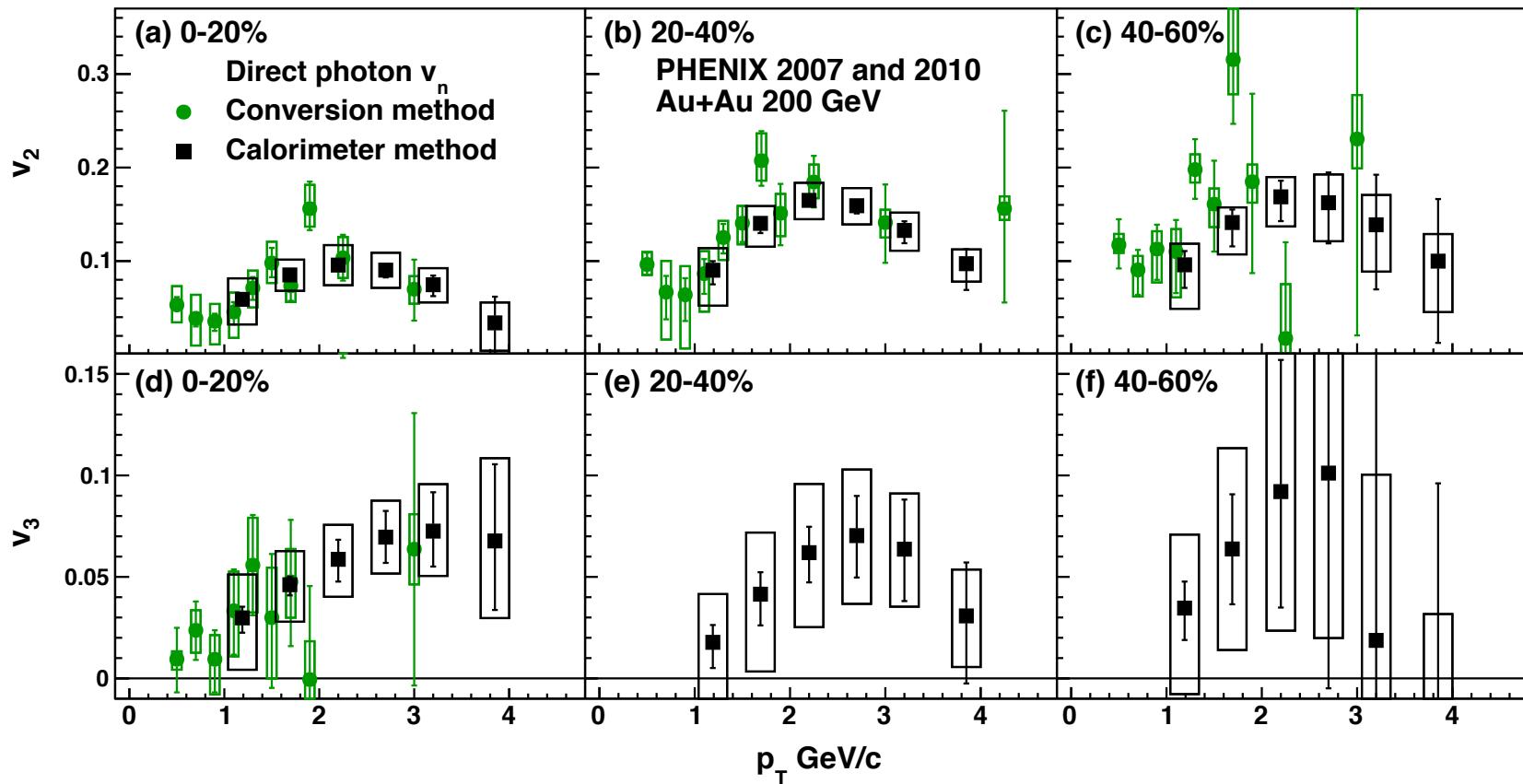


Direct photon v_n

$$v_n^{dir} = \frac{R_\gamma v_n^{inc} - v_n^{dec}}{R_\gamma - 1}$$

NEW

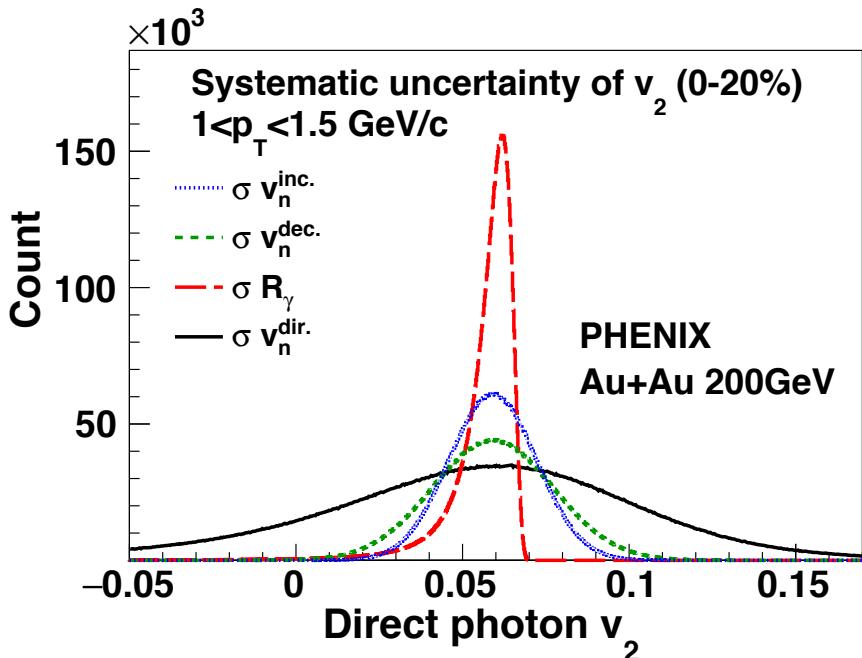
arXiv:1509.07758



Systematic Uncertainties on v_n

$$\sigma_{v_n^{dir}}^2 = \left(\frac{R_\gamma}{R_\gamma - 1} \right)^2 \times \sigma_{v_n^{inc}}^2 + \left(\frac{1}{R_\gamma - 1} \right)^2 \times \sigma_{v_n^{dec}}^2 + \left(\frac{v_n^{dec} - v_n^{inc}}{R_\gamma - 1} \right)^2 \times \sigma_{R_\gamma}^2 + \sigma_{EP}^2$$

- Revisited systematic uncertainty calculation based on discussions with ALICE
- Non-linear dependence of uncertainty on R_γ
 - Asymmetric uncertainties
- Model probability distributions with MC



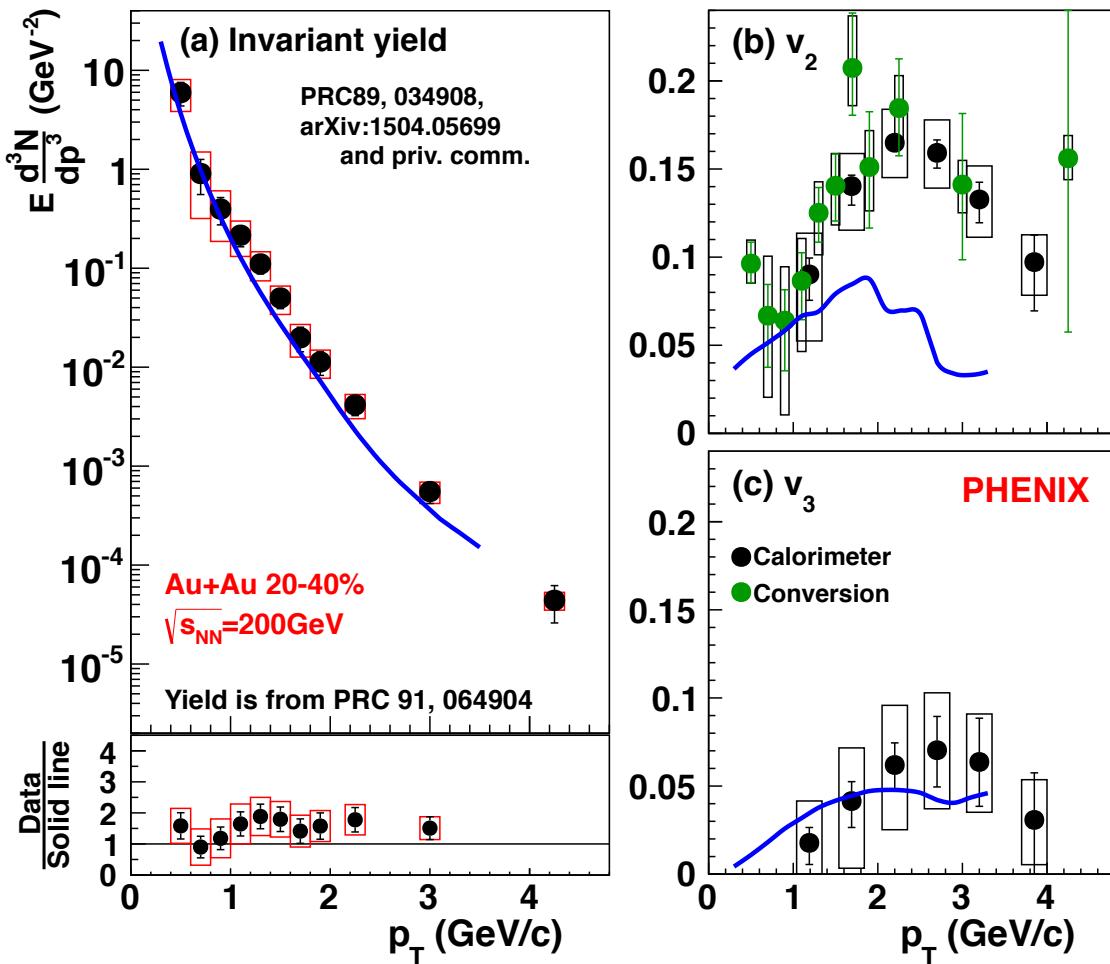
Source	0-20%	20-40%	40-60%	Type
R_γ (from [3])	5.5%	5.5%	5.5%	B
v_2^{inc} inclusive photons				
conversion method	<1%	<1%	<1%	B
calorimeter method	4%	3%	4%	B
v_2^{dec} decay photon				
meson v_2 (stat)	<1%	<1%	<1%	A
$\pi^0 v_2$ (sys)	5%	3%	2%	B
$\eta, \omega v_2$ (sys)	<1%	<1%	<1%	B
Event plane				
	3%	3%	3%	C
v_3^{inc} inclusive photons				
conversion method	<1%	<1%	<1%	B
calorimeter method	5%	7%	10%	B
v_3^{dec} decay photon				
meson v_3 (stat)	1%	2%	4%	A
$\pi^0 v_3$ (sys)	11%	11%	11%	B
$\eta, \omega v_3$ (sys)	$\sim 1\%$	$\sim 1\%$	$\sim 1\%$	B
Event plane				
	6%	7%	18%	C

What do we learn from these results? --model calculations--

- Models on the market (non-exhaustive list)
 - Thermal photon rate in QGP, hadron gas, prompt production folded with time evolution (viscous/non-viscous hydro, blastwave expansion, etc)
 - H. van Hees, C. Gale, R. Rapp, Phys. Rev. **C84** 054906 (2011)
 - H. van Hees, M. He, R. Rapp, Nucl. Phys. **A933** 256 (2015)
 - C. Shen, U. Heinz, J.F. Paquet, I. Kozlov, C. Gale Phys. Rev. **C91** 024908 (2015)
 - Modifications of formation time and initial conditions
 - R. Chatterjee, H. Holopainen, I. Helenius, T. Renk, K.J. Eskola, Phys. Rev **C88**, 034901 (2013)
 - F.M. Liu, S. X. Liu, Phys. Rev **C89**, 034906 (2014)
 - G. Vujanovic et. al, Nucl. Phys. **A932**, 230 (2014)
 - Enhanced non-equilibrium effects (glasma, etc.)
 - A. Monnai, Phys. Rev. **C90**, 021901 (2014)
 - L. McLerran and B. Schenke, Nucl. Phys. **A929**, 71 (2014)
 - F. Gelis, H. Niemi, P.V. Ruuskanen, S.S. Rasanen, Journal of Physics **G30**, S1031 (2004)
 - Enhanced early emission from magnetic field
 - B. Mueller, S.Y. Wu, D.L. Yau, Phys. Rev **D89** 026013 (2014)
 - K. Tuchin, Phys. Rev. **C87** 024912 (2013)
 - G. Basar, D. E. Kharzeev, V. Skokov, Phys. Rev. Lett **109** 202303 (2012)
 - Microscopic transport (PHSD)
 - O. Linnyk, W. Cassing, E.L. Bratkovskaya, Phys. Rev. **C89**, 034908 (2014)
 - Enhanced emission at hadronization
 - S. Campbell, Phys. Rev. **C92** 014907 (2015)

Theory Comparison: Microscopic transport model

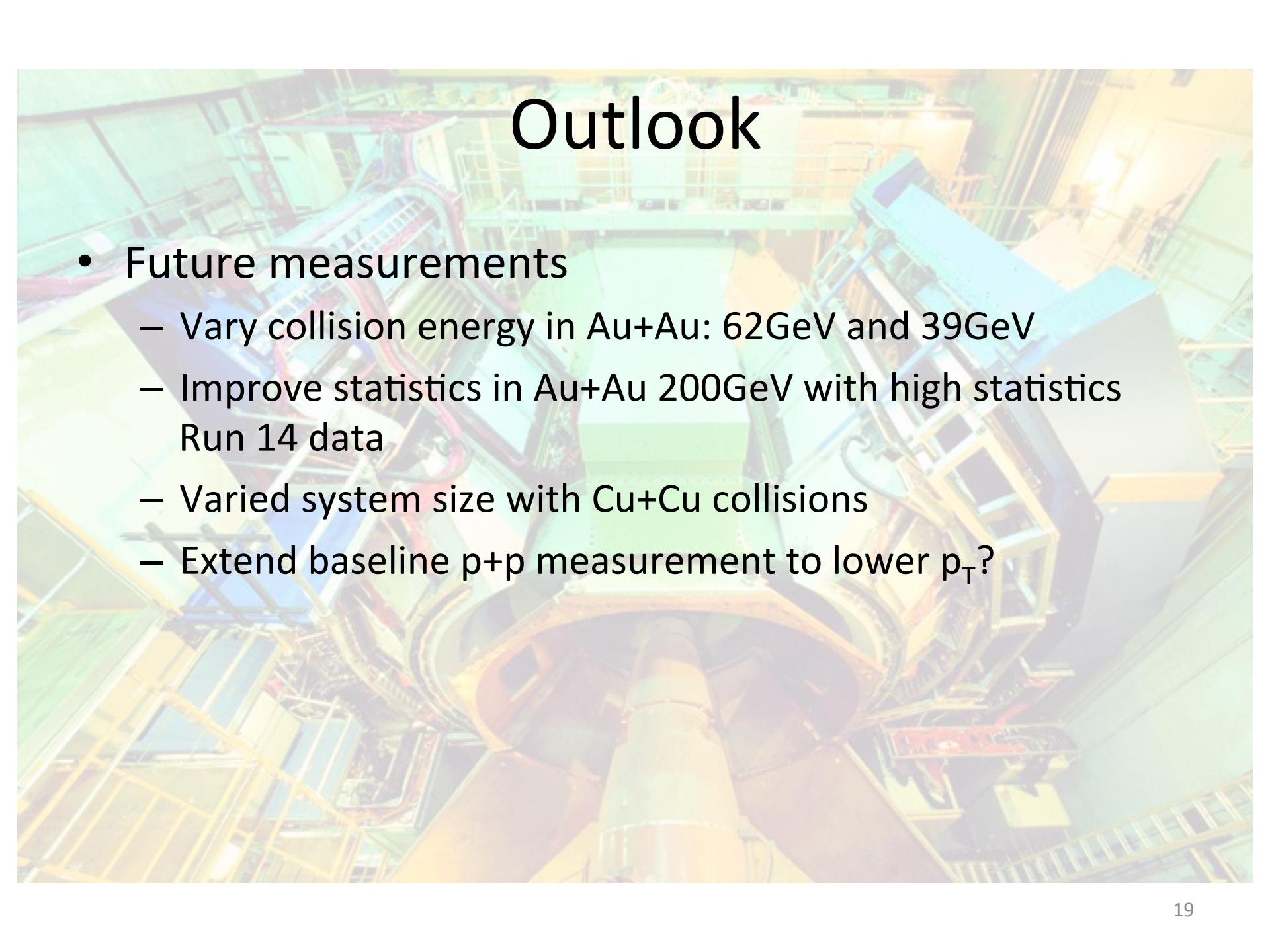
- PHSD
 - Parton-Hadron-String Dynamics model
- microscopic transport for evolution
- includes large contribution from hadron-hadron interactions in HG using Boltzmann transport
- thermal photon from QGP included



*please see paper (or backup slides) for more model comparisons

Conclusions

- PHENIX has detailed measurements of the direct photon yield, v_2 , and v_3 in $\sqrt{s}=200\text{GeV}$ Au+Au collisions
- An excess of yield above the N_{coll} scaled p+p yield is observed at all centralities down to 400MeV/c in photon p_T (up to about 3GeV/c)
 - Shape of excess is independent of centrality
 - Yield scales as $N_{\text{part}}^{1.38}$
- Observe a sizable v_2 and v_3
- Theoretical picture is still incomplete
- Comparing models to both yield and v_n together implies that later-time emission is significant



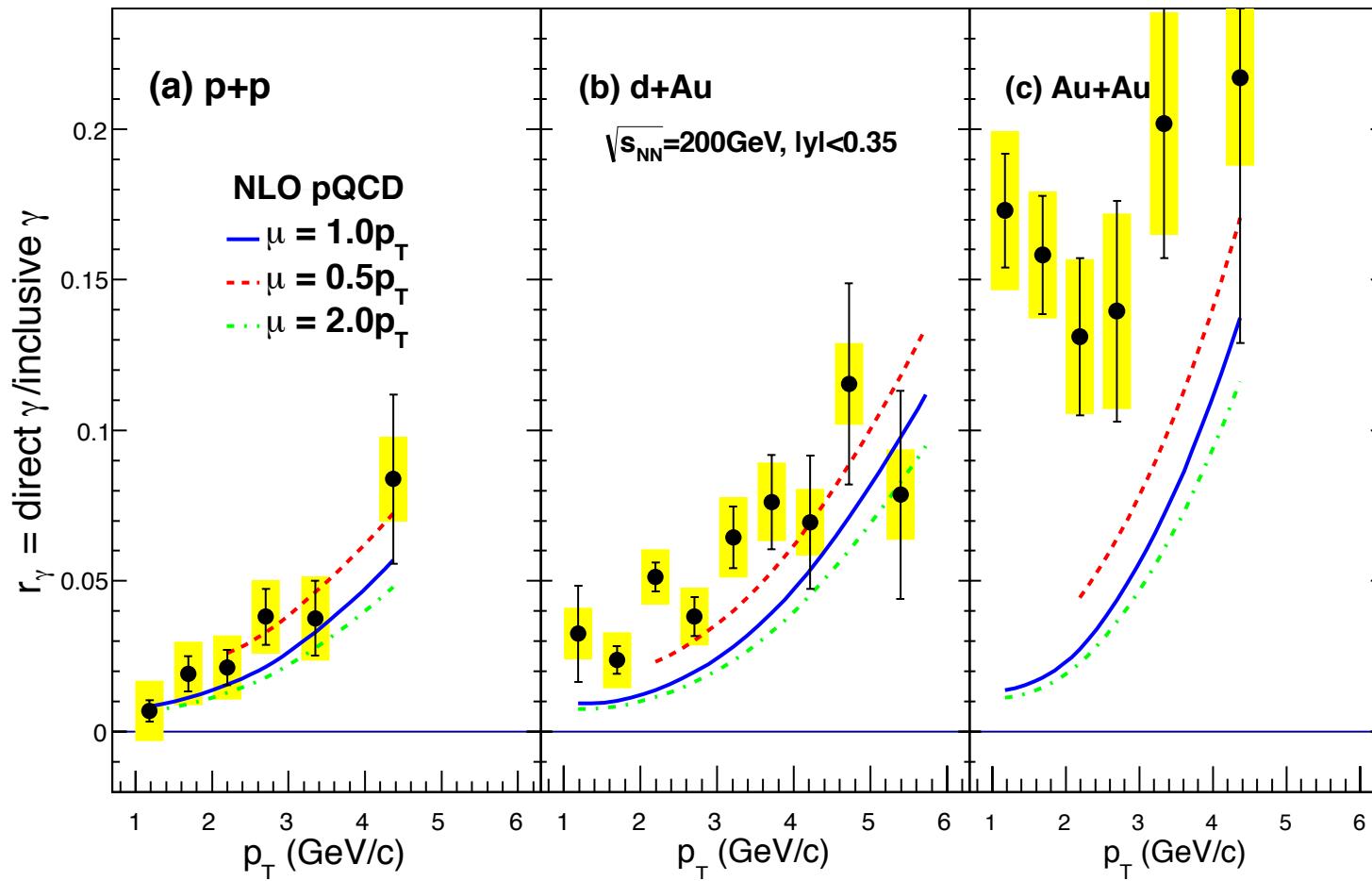
Outlook

- Future measurements
 - Vary collision energy in Au+Au: 62GeV and 39GeV
 - Improve statistics in Au+Au 200GeV with high statistics
Run 14 data
 - Varied system size with Cu+Cu collisions
 - Extend baseline p+p measurement to lower p_T ?

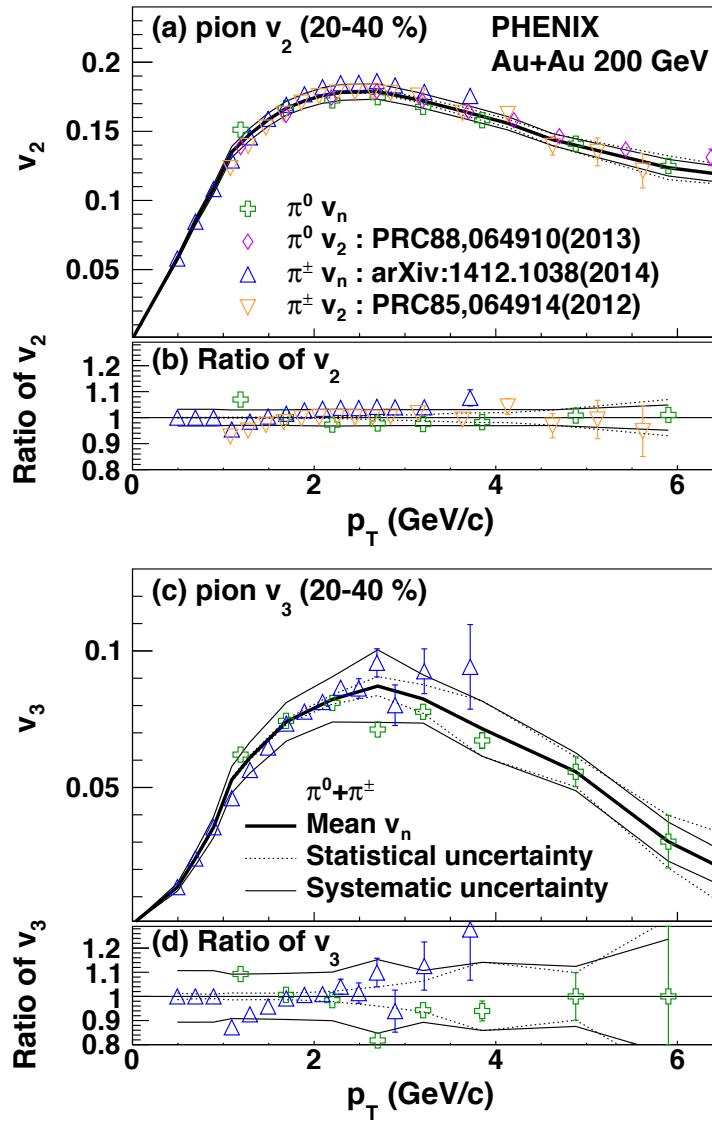
Backups

Direct Photons in Different Systems

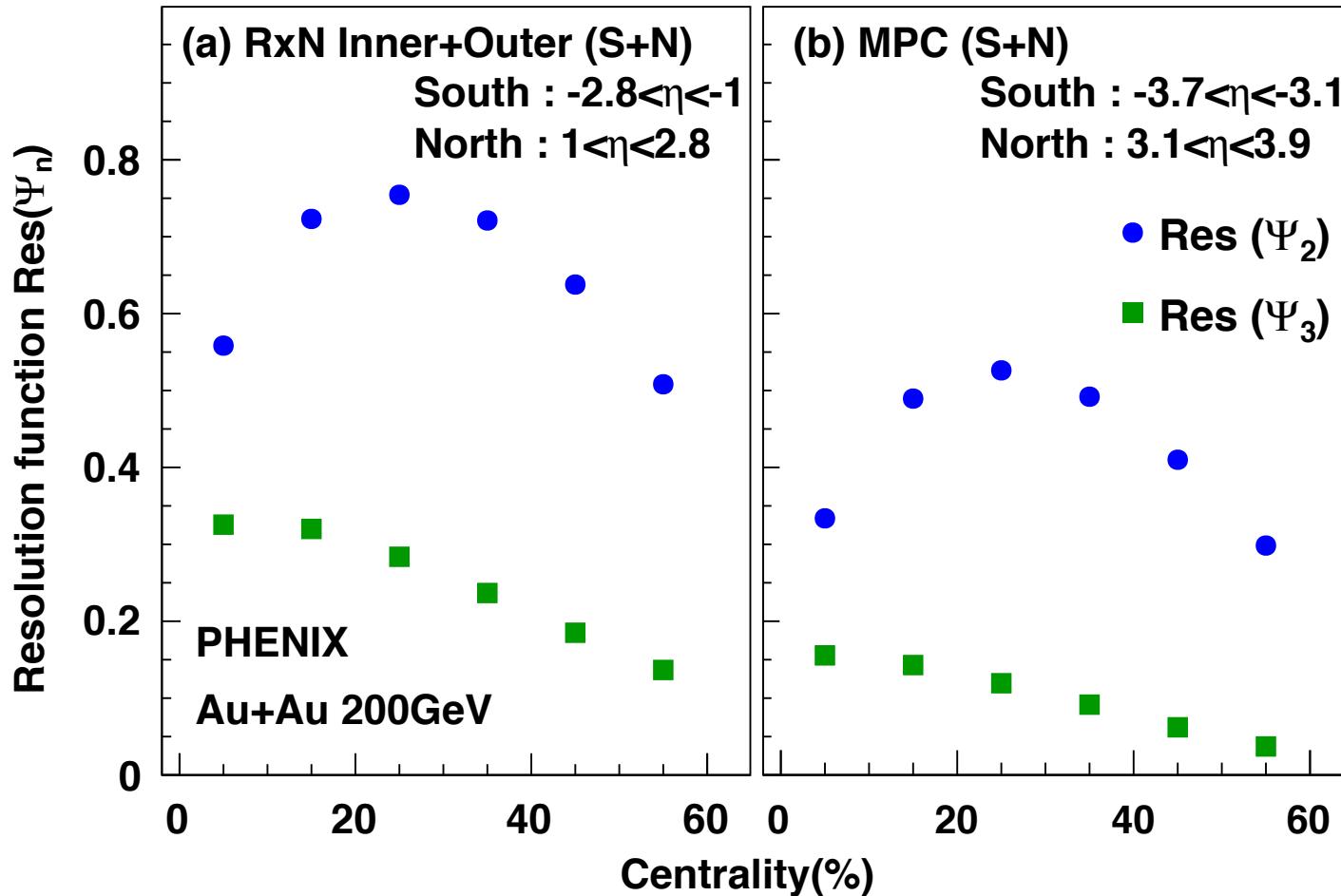
PHENIX: Phys.Rev. C87 (2013) 054907



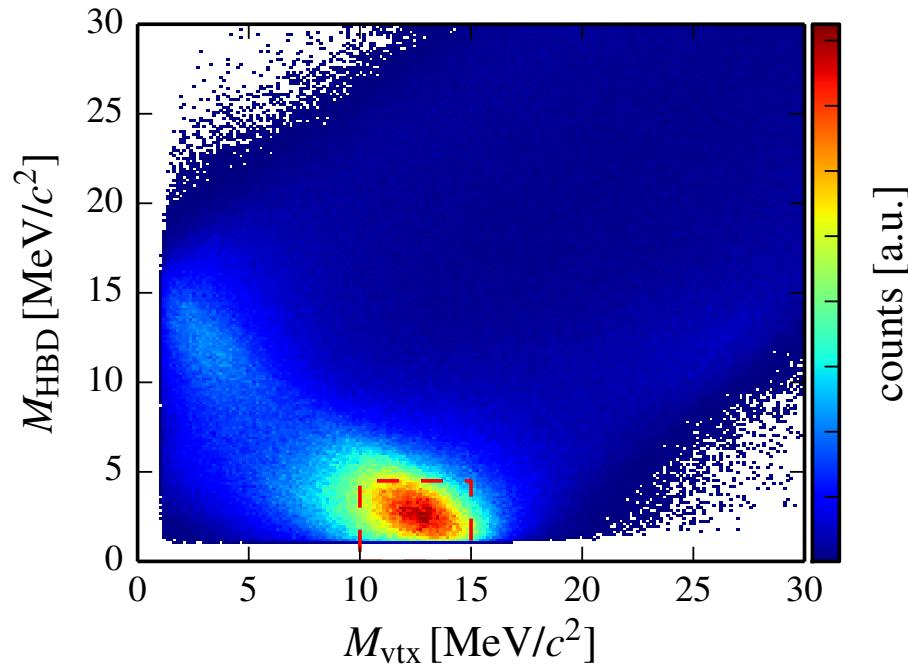
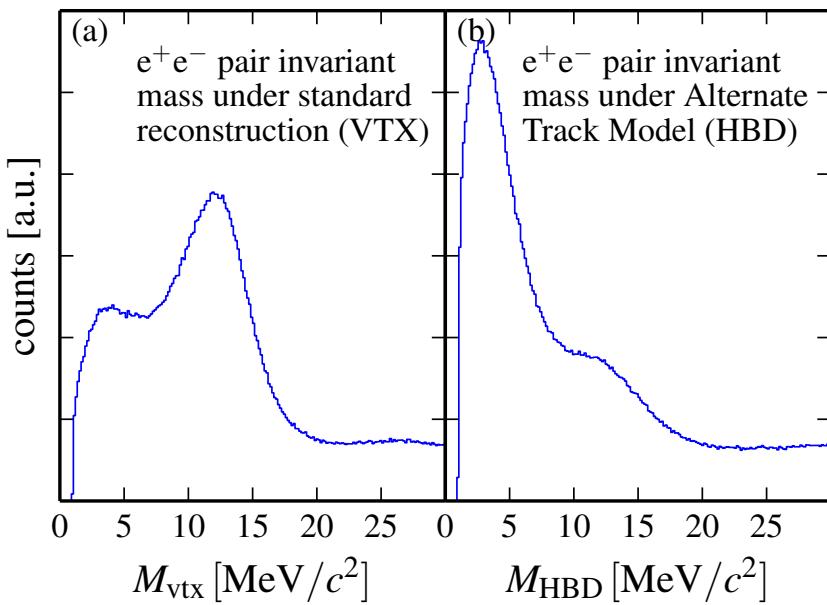
decay photon v_n cocktail



Reaction plane resolution



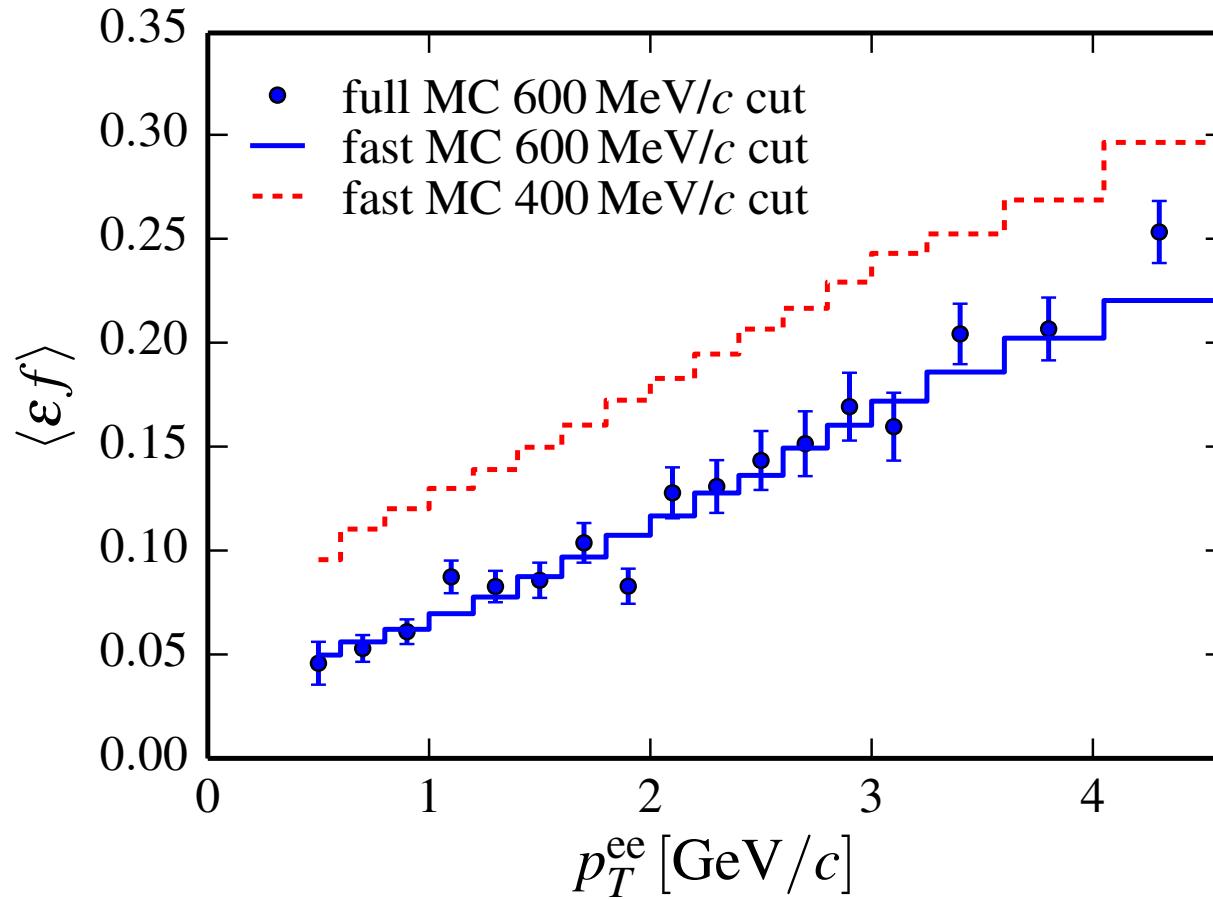
conversion photon id details



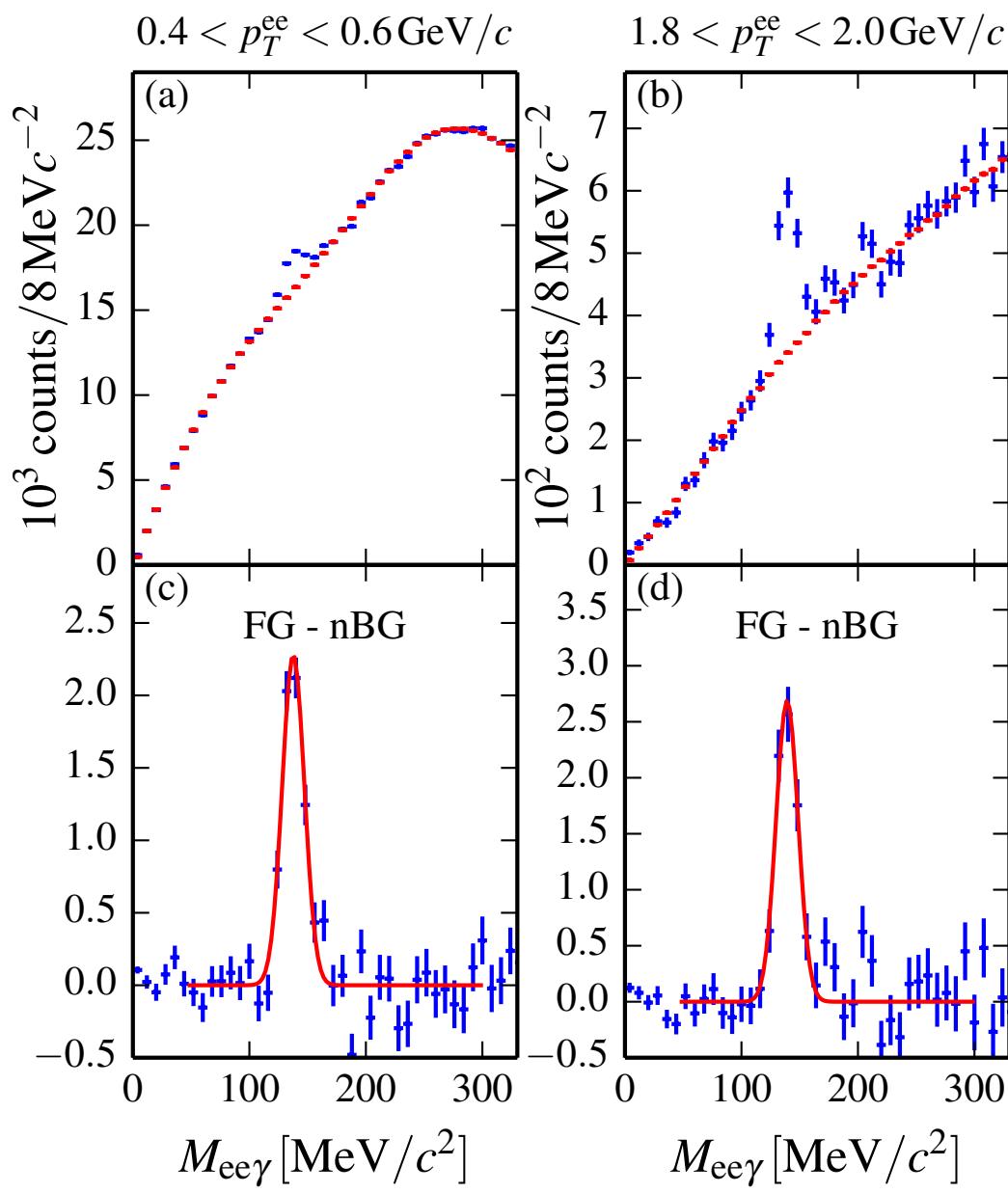
- focus on conversions in the backplane of the HBD
- momentum of far off-vertex particles are mis-reconstructed
 - due to PHENIX reconstruction assuming event vertex as origin
- leads to an artificial mass (that is dependent of radius of conversion)
- model this mis-reconstruction in a MC
- allows for both a correction of the mis-reconstruction and a cut space for id

correction for R_gamma

- pion decay photon tagging efficiency and acceptance



pion yield
measurement from
the conversion
analysis



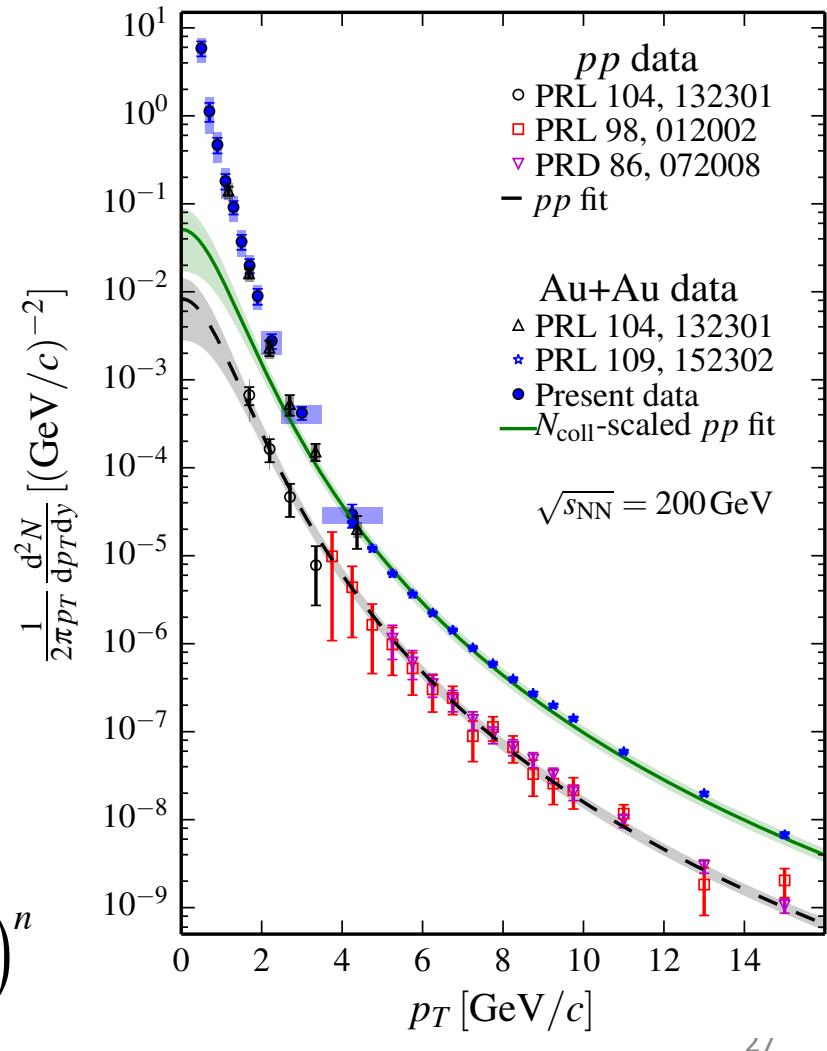
Fit to the p+p Data

$$\frac{dN}{dy} = a \left(1 + \frac{p_T^2}{b} \right)^c$$

- with
- $a = (8.3 \pm 7.5) \times 10^{-3}$
- $b = 2.26 \pm 0.78$
- $c = -3.45 \pm 0.08$

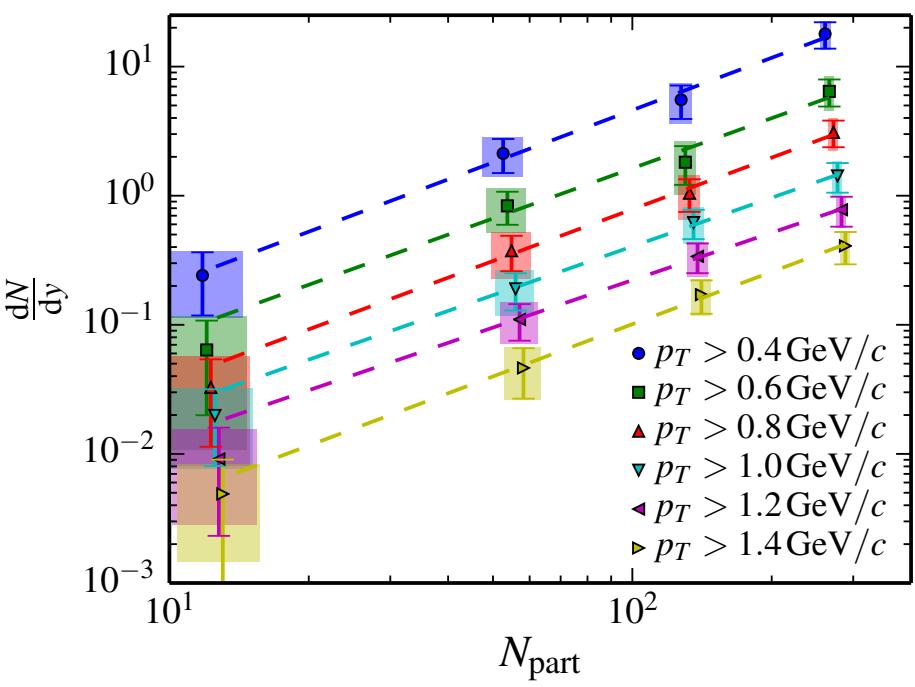
Systematics include:

- pure power law: $\frac{a}{p_T^n}$
- NLO inspired: $a \cdot p_T^{-(b+c \ln x_T)} \cdot (1 - x_T^2)^n$
with $x_T = 2 p_T \sqrt{s}$

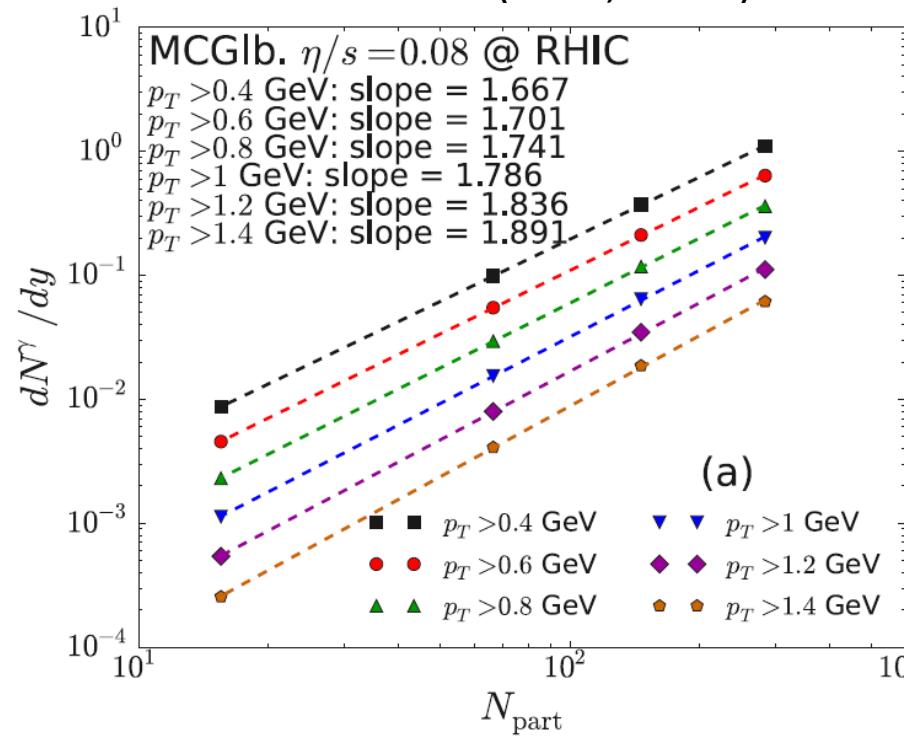


Theory Comparison of N_{part} Dependence of Yield

PHENIX: PRC **91**, 064904 (2015)

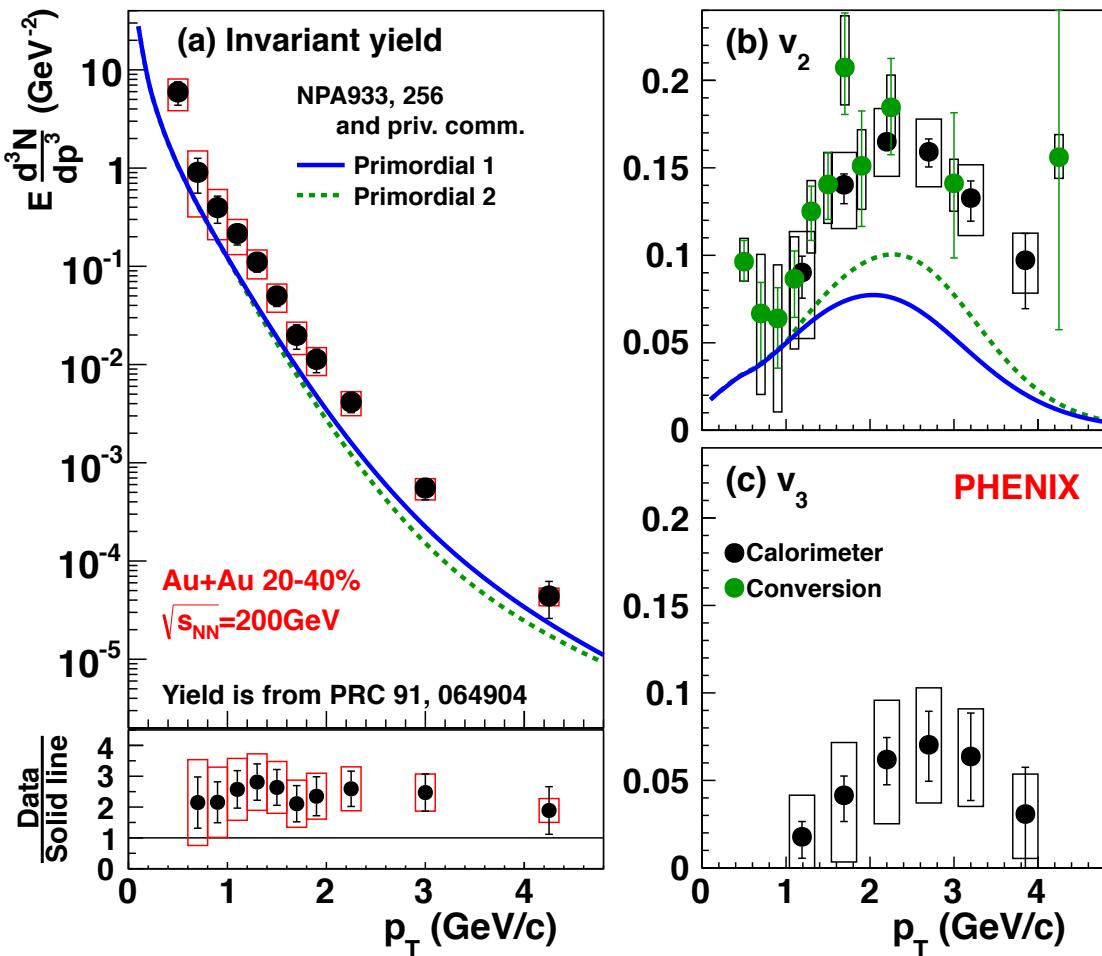


PRC 89 044910 (Shen, Heinz)



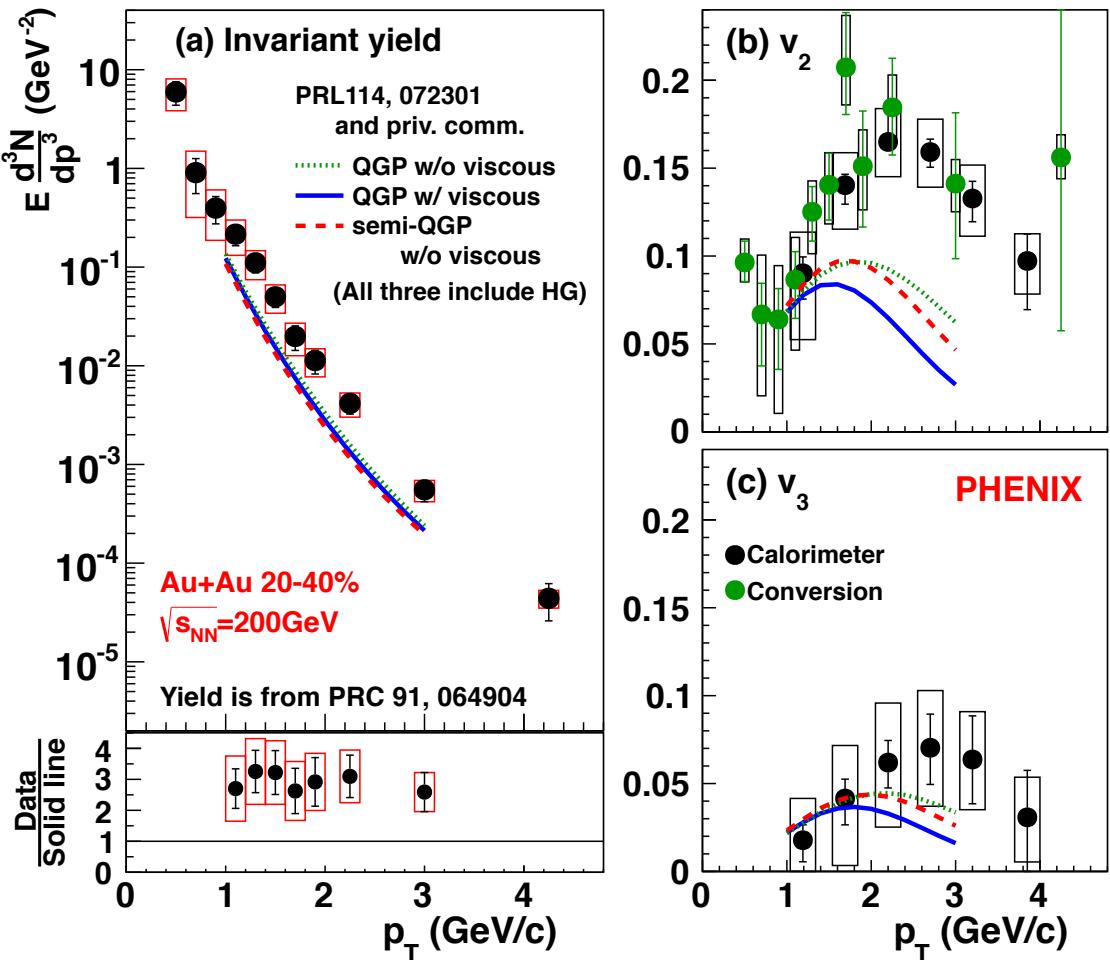
Theory Comparison: Fireball scenario

- Incl pQCD, QGP and HG
- Ideal hydro evolution
- Includes finite initial flow at thermalization
- Blue-shift included
- Includes resonance decays and hadron-hadron scattering
- No v_3 calculation

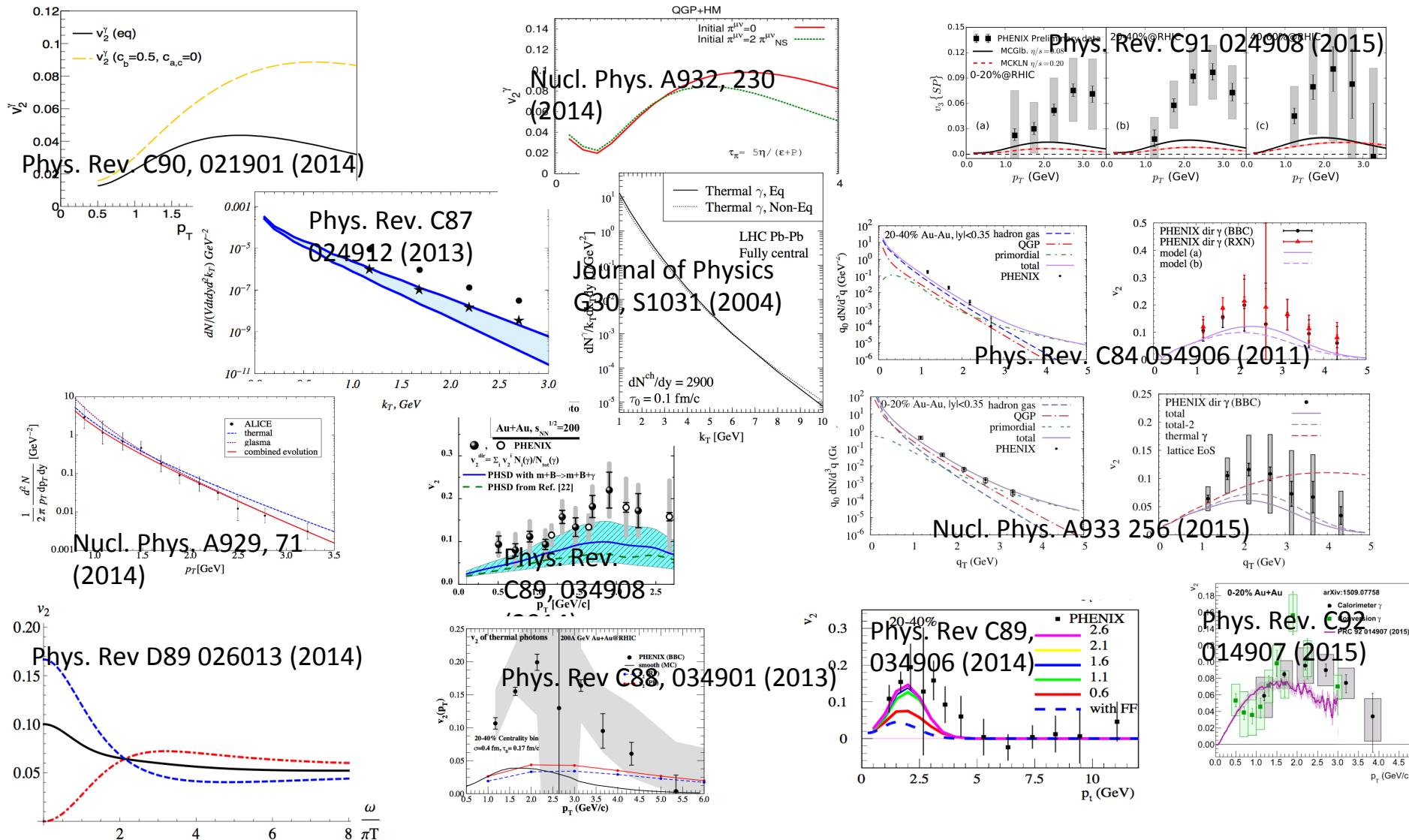


Theory Comparison: Semi-QGP scenario

- full viscous hydro evolution
- semi-QGP is the QGP near T_c
 - photon production evaluated at each T
 - T -dep. Polyakov loop is taken into account and summed over $T_i > T > T_c$
- photons from semi-QGP with HG is included
- annihilation and Compton processes around the hadronization time are naturally included



Lots of Theoretical Interest



Disentangling various photon sources

- We measure a time-integrated view of all of this!
- More differential measurements would disentangle the photon production sources

Sources	p_T	v_2	v_3	v_n t-dep.	
Magnetic field	All p_T	Positive down to $p_T=0$	Zero		
Primordial (jets)	High p_T	~zero	~zero		
QGP (thermal)	Mid p_T	Positive and small	Positive and small		
Jet-Brems.	Mid p_T	Positive	?		
Jet-photon conversion	Mid p_T	Negative	?		
Hadron-gas (thermal)	Low p_T	Positive and sizable	Positive and sizable		